UDC 551.5 : 551.465.7 : 551.507.362.2 : 551.553.21(540)

SATELLITE EVIDENCE OF SEA-AIR INTERACTIONS DURING THE INDIAN MONSOON

K. RAGHAVAN

Institute of Tropical Meteorology, Poona, India

ABSTRACT

A cloud-free zone adjoining the Indian Peninsula, observed from Gemini XI on Sept. 14, 1966, is attributable to upwelling. A possible connection between a weak southwest monsoon, coastal upwelling, and below-normal rainfall is suggested.

1. INTRODUCTION

Perhaps the most spectacular cloud photograph (fig. 1) taken over the Indian region from a spacecraft is the one by U.S. Astronaut Richard Gordon with a hand-held camera.

The photograph reveals a region remarkably free from clouds around Peninsular India. The cloudless zone is 60 to 100 km in width along the west coast and continues around the southern tip of India into the Bay of Bengal. The cloudless zone is at its maximum width in the Bay extending toward the northern half of the coastal seas of Ceylon. Here, the cloudless zone is about 3° of longitude (300 km) wide along the Indian coast. This zone is, strictly speaking, not totally cloud-free because of a whiff of cirrus spreading about. Farther north along the east coast of India, the cloudless zone decreases in width to about 150 km.

Gemini XI passed over this region when the area was under the influence of a weak monsoon. Normally during such periods cloud is negligible but we find from figure 1 that there was extensive clouding in the seas. This could be perhaps attributed mainly to the upper air troughs, one over the Arabian Sea and another over the Bay of Bengal, at 850 and 700 mb.

It is very unfortunate that this peculiar cloud pattern, which might have provoked serious thinking among several meteorologists, was observed over an oceanic region having, normally, a poor observational network.

The purpose of this note is to present all the available relevant observational materials, published and unpublished, and initiate a discussion on the possible causes for the cloud phenomenon. How far this phenomenon is important to the study of the monsoon circulation is also considered.

2. COASTLINE INFLUENCE

The most curious feature of the cloud pattern depicted by figure 1 is the cloudless zone skirting the coastline. The absence of cloud tempts us to believe, in the first instance, that it is a zone of few or no upward currents. A careful examination of the boundary of offshore clouding indicates that the cloud boundary had a remarkable tendency to follow the contour of the coastline, particularly in the Arabian Sea. This observation suggests that the cloudless zone is mainly influenced by the coastline and, to understand this, one must consider the low-level circulation that depends on the configuration of the coastal boundary.

The sea breeze is one such circulation that is controlled by the coastal boundary. When the air over the land is warmer than the air over the sea, a pressure gradient is set up so that the air from the sea blows onshore. Over the land, the sea breeze is warmer and ascends, sometimes up to 1 or 2 km in the Tropics. The ascending air moves seaward in the higher levels as a current counter to the sea breeze and sinks over the cooler sea. Thus, a sea-breeze circulation is constituted of a rising motion over the land and a sinking motion over the coastal seas.

In the Tropics a sea-breeze circulation system, in its well-developed stage, can extend from 100 to 150 km seaward to about 100 to 200 km inland. In India (Nicholson and Dixit, 1964; Ramanathan, 1931), this is more or less the maximum dimension so far observed. The land breeze that replaces the sea breeze is smaller in dimensions and weaker in intensity.

During the monsoon season, sea and land breezes are masked by the seasonal winds. However, when the monsoon weakens, they are distinctly observed.

In addition to the sea breeze, coastal upwelling is a phenomenon that may influence the low-level atmospheric circulation depending on the orientation of the coastline. When the surface wind blows over the sea for a period of time, it causes the light surface waters to drift away as wind-driven currents. Due to the Coriolis force, the wind currents in the Northern Hemisphere set about 45° to the right of the direction of the surface wind that produces them. If the wind currents make an angle of less than 45° with the coast and the surface waters drift away from the coast, coastal upwelling takes place. Normally the region of upwelling is restricted to a distance of about 100 to 150 km from the coast, but the cold waters are sometimes observed as far away as 400 to 500 km. It has been shown by Yoshida (1967) that, in shallow seas, upwelling can occur over a larger area.

When the sea is colder than the adjacent air (due to upwelling), the flux of heat is from the air to the sea, leading to progressive cooling and shrinking of the lower levels of the atmosphere. Over this level of shrinking air

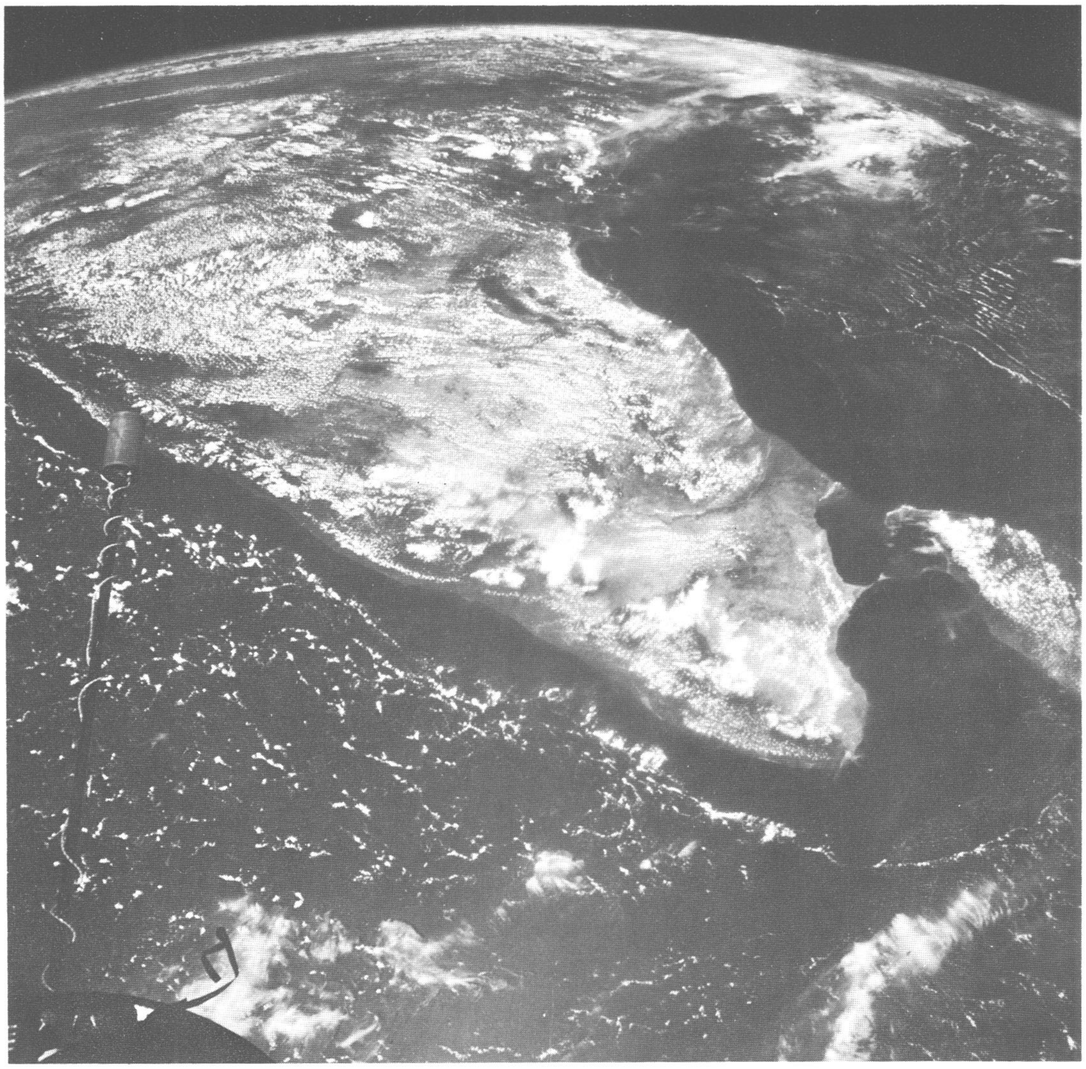

FIGURE 1.—NASA photograph taken by Astronaut Richard Gordon aboard Gemini XI at an altitude of about 850 km at 0735 GMT on Sept. 14, 1966.

mass, warmer air rising from the surrounding areas may sink and inhibit cloudiness.

3. GORDON'S CLOUD PATTERN

An examination of the anemographic records at the Panambur Harbor Project (12°57′ N., 74°50′ E.; 16.5-m height of Dines pressure tube anemograph) representing the west coast and at Madras Harbor (13°04′ N., 80°15′ E.; 33.0-m height of Dines pressure tube anemograph) representing the east coast shows that sea breeze set in along the coasts before Astronaut Gordon took the photograph at 0735 GMT on Sept. 14, 1966. On the west coast, the sea breeze set in at about 0530 GMT and on the east coast by 0630 GMT. An important question to be examined now is whether Gordon's cloud pattern had its genesis before the sea breeze set in. On this day at 0343 GMT, ESSA 2 transmitted an APT cloud picture that was unfortunately not suitable for photographic reproduction. One could, however, observe therein certain broad features of clouding that are roughly indicated in figure 2. Over the seas, the types of clouds are believed to be more or less the same (low and medium) as observed over the land at 0300 GMT. The APT picture was too poor to give an idea of the clouding along the east coast. For our purpose, figure 2 is, nevertheless, sufficient proof that before the sea breeze set in the cloud pattern was getting organized with the coastal seas nearly free of clouds. Even after the sea breeze set in, its contribution to the cloudless zone (which cannot be ruled out) appears limited as one may infer from the cloudless zone near Ceylon; here, an extension of about 300 km (fig. 1), perhaps too large for the sea breeze to influence, occurred.

Let us next consider the coastal upwelling. By September 10 the surface flow of air in the Arabian Sea and Bay of Bengal became anticyclonic, a condition typical of a weak monsoon. With decreasing clouds and rain, surface temperature steadily increased on the Peninsula, and the sea and land breezes became more distinct. Probably under

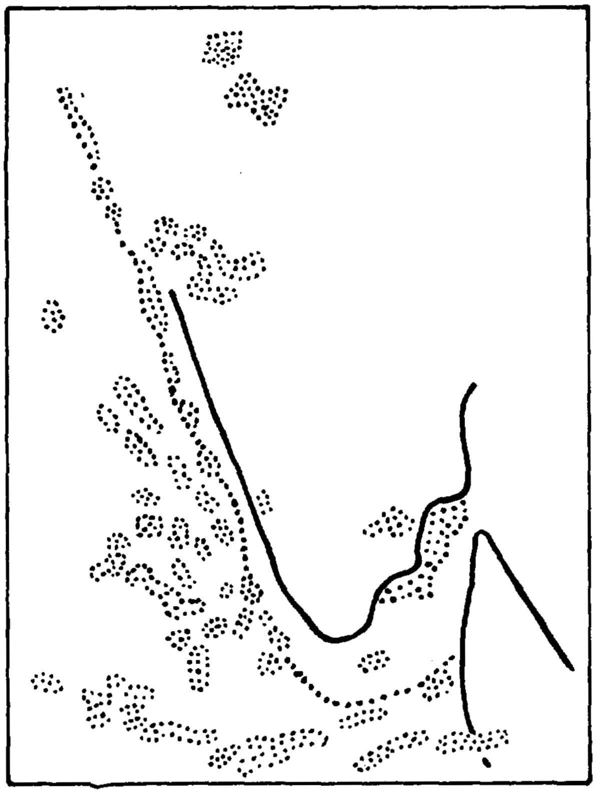

FIGURE 2.—ESSA 2 nephanalysis at 03 hr 43 min 51 sec GMT on Sept. 14, 1966.

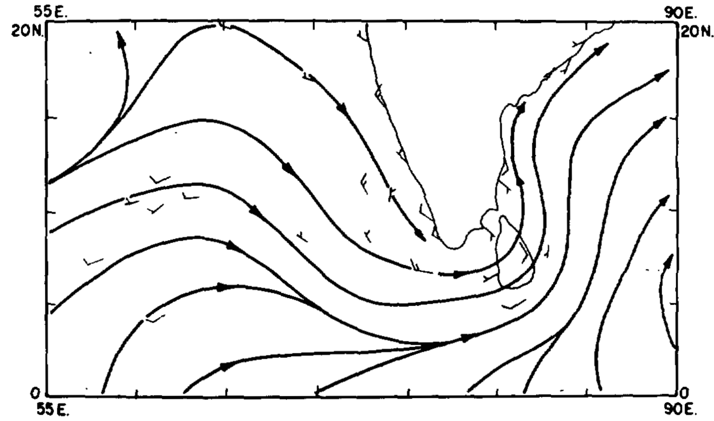

FIGURE 3.—Surface winds at 12 GMT on Sept. 14, 1966.

TABLE 1.—*Air minus sea temperature (°C) in the Arabian Sea and Bay of Bengal*

Day (Sept. 1966)	Arabian Sea (° C)	Distance from west coast (km)	Bay of Bengal (° C)	Distance from east coast (km)
11	0.5	600		
12	0.5	700	0.5	900
13			0.5	250
			1.5	700
14	1.0	500		

the influence of the anticyclonic flow over the seas, the sea and land breezes had a more northerly component in the west coast and a more southerly component in the east coast. The coastal wind system was thus favorable for causing upwelling day and night, beginning Sept. 11, 1966. Figure 3 represents the type of wind regime that prevailed.

Within 100 km of the coast, where the influence of coastal upwelling is usually a maximum, there were no sea-surface temperature observations during this period. Examination of past records has revealed the rather disturbing fact that most of the ships, Indian and foreign, very seldom record sea-surface temperature within 100 km of the coast. During the period of Sept. 11 to 14, 1966, temperatures were recorded by ships situated more than 200 km from the Indian coast. The differences between air and sea-surface temperatures are shown in table 1. These observations are significant since they show that during this period the sea surface was colder than the air. Considering these observations and the coastal winds, it seems reasonable to believe that there was upwelling all along the Indian coast, reducing the surface temperature of coastal waters significantly below the air temperature. In that case, it seems probable that the cold waters of upwelling areas cooled the lower levels of the atmosphere sufficiently to cause sinking motion by the morning of September 14. ESSA 2 indicated on that day that the clouds over the coastal seas were dissipating rapidly at 0343 GMT. Within about 4 hr, Gordon reported that the low-medium clouds over the entire coastal seas had completely dissipated. The cloudless zone, naturally, covered a larger area over the southwestern part of the Bay where the shallow sea is favorable for extensive upwelling. Thereafter, the surface winds were rather variable as a prelude to the withdrawal of the monsoon within a few days. The cloud pattern became disorganized, and its last remnants were reported by Nimbus II on September 16 at 0552 GMT (fig. 4).

4. IMPORTANCE OF SEA-AIR INTERACTIONS

The periodic increase and decrease of the southwest monsoon rainfall over India has been a problem of investigation for several decades. In this connection, many have studied atmospheric circulations at different levels as high as the midstratosphere. The lowest layer of the atmosphere, however, remains practically unexplored. This layer close to the sea is very important since it is solely responsible for transporting moisture and heat from the sea to the higher atmosphere.

It is usually observed that when there is a prolonged weak monsoon over India the surface winds in the eastern part of the Arabian Sea are from a northerly direction, tending to be parallel to the west coast. Such winds are favorable for coastal upwelling, and our present study leads us to believe that the subsurface cold waters

FIGURE 4.—Nimbus II APT cloud picture at 05 hr 52 min 27 sec GMT on Sept. 16, 1966.

prevail in the eastern part of the Arabian Sea during periods of weak monsoon. In the eastern part of the Arabian Sea, the cold waters would inhibit upward flux of heat and moisture. Does this contribute to a general decrease of rainfall in India? One may be tempted to examine this seriously on considering that the surface winds in the eastern part of the Arabian Sea back to a direction (west or southwest) unfavorable for coastal upwelling before the monsoon revives and rainfall increases. Moreover, the revival of the monsoon normally takes place in the eastern part of the Arabian Sea earlier than elsewhere.

ACKNOWLEDGMENTS

I am thankful to Prof. Sverre Petterssen for his remarks and suggestions and to Dr. K. R. Saha and Mr. K. V. Rao for their helpful discussion during the course of this investigation.

REFERENCES

Nicholson, J. R., and Dixit, C. M., "The Sea Breeze at and near Bombay," *Indian Journal of Meteorology and Geophysics*, Vol. 15, No. 4, Oct. **1964** pp. 603–608.

Ramanathan, K. R., "The Structure of Sea Breeze at Poona," *India Meteorological Department Scientific Note*, Vol. 3, No. 30, Poona, **1931**, pp. 131–134.

Yoshida, K., "Circulation in the Eastern Tropical Oceans With Special References to Upwelling and Undercurrents," *Japanese Journal of Geophysics*, Vol. 4, No. 2, Mar. **1967**, pp. 1–75.

[Received April 11, 1969; revised May 27, 1969]